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Work-Hardening And Effective Viscosity In Solid Beryllium

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WORK-HARDENING AND EFFECTIVE VISCOSITY IN SOLID BERYLLIUM

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Abstract

Results from Hopkinson split-bar, plate-impact, and cylinder deceleration experiments on beryllium are compared with hydrodynamic computer code simulations. By substantially increasing the beryllium work-hardening in the Steinberg-Guinan constitutive model, excellent agreement between the experiments and the calculations is achieved. A model to estimate effective viscosity is also proposed and the resultant calculations are in reasonable agreement with those derived from another model advanced by Asay, Chhabildas and Wise.

[62.50.+p, Beryllium, Work-Hardening, Viscosity]

Introduction

As part of a program to understand the equation of state of beryllium, three different kinds of deformation experiments were performed. These were Hopkinson split-bar compression (uniaxial stress), plate-impact (uniaxial strain), and cylinder deceleration experiments (two-dimensional flow).

Previous papers [1,2] have described the elastic-viscoplastic constitutive model in our hydrodynamic computer codes. Work-hardening is described by a function $(1+\beta\varepsilon)^n$ with $Y_o(1+\beta\varepsilon)^n \leq Y_{max}$. Y is the yield strength, subscript o refers to the Hugoniot elastic limit, and subscript max to the maximum work-hardened strength at STP conditions. ε is the equivalent plastic strain, and β and n are unique parameters for each material. Our previous limited data for beryllium implied that β=81 and n=0.22, but computer simulations of the above experiments were poor when these parameters were used.

One purpose of this paper is to show that with new work-hardening parameters, our hydrodynamic codes can simulate these experiments very well. A second purpose is to estimate solid viscosity using the information contained in the constitutive model and the additional relation that the effective viscosity, ν, is equal to $2G\tau$ where G is shear modulus and τ is a time constant.

Work-Hardening

Hopkinson split-bar experiments yield what is probably the least ambiguous, high-strain-rate work-hardening data. Breithaupt [3] has performed a series of such experiments with strain rates reaching 2500 $^{-1}$. The data are shown as true stress - true strain in Fig. 1. They can be fit very well with β=26 and n=0.78. The low strain data can be extrapolated to zero strain and the stress at this point is in excellent agreement with the Hugoniot elastic limit data of Christman and Feistmann [4]. The work-hardening maximum of 1.31 GPa is also in good agreement with the work of Reicker, Towle and Rooney [5] who got 1.23 GPa by a different technique which slightly underestimates Y_{max} [6].

Breithaupt's results also compare favorably with the data of Green and Schierloh [7], and Nicholas and Sever [8] on type S-200 beryllium. Unfortunately,these data were not found until after our work was completed.

Asay, Chhabildas and Wise performed plate-impact experiments with initial loading stresses between 6.4 and 34.4 GPa [9]. A velocimeter recorded the velocity of a beryllium-LiF interface.

Fig. 2 shows the experimental interface velocity vs time wave profile for a typical shock and release experiment. In the same figure is the hydrodynamic code simulation. Using β, n and Y_{max} as determined from the Hopkinson split-bar experiments, one can see that the simulation agrees very well with the data [10]. A calculational comparison has also been made using the old work-hardening parameters. In this case, it is easy to see that the release is not calculated correctly.

Fig. 3 is a plot of yield strength vs. pressure for all the experiments.

Honodel [11] did a series of experiments where he impacted beryllium cylinders against a "stone-wall". For one of these experiments the post-shot sample was sectioned and photographed to clearly delineate its shape. Measurements of the shape were made and this experimental profile is shown in Fig. 4.

Two-dimensional hydrodynamic calculations were done using the old and new work-hardening models. The results of these calculations are shown in Fig. 4. In the fracture-free zone, the biggest difference between the new model and the experimental data is ~ 35 µm. This discrepancy can be accounted for in the uncertainty in measuring the post-shot profile. However, in the fracture zone, the good agreement between the data and the new model calculation is probably fortuitous.

Estimating Solid Viscosity

In Ref. 1, G is given as $G_0(1+A\eta^{-1/3}P-B\Delta T)$ where G_0 is the initial shear modulus, η is compression, P is pressure, ΔT is the change in temperature and A and B are material constants. From Ref. 2, τ can be described, in an equilibrium state behind the shock front, by Cexp[D/T] where C and D are material constants. The values of A, B and D are determined a priori from other data, but C was found by normalizing a computer simulation to the stress-loading part of one of the low-pressure wave-profiles in Ref. 4.

Additional computer simulations, similar to those shown in Fig. 2, were then done for all the data of Wise et al. [9] and Christman and Feistmann [4] and the values of G and τ determined. In Fig. 5, $\nu=2G\tau$ is plotted as a function of the measured value of maximum strain rate, $\dot{\varepsilon}_p$. For peak strain rates in excess of ~ $60\mu s^{-1}$ (peak stress about 25 GPa) the computer simulations become affected by the artificial viscosity, Q. A plot of $Q_{max}\,\Delta t$, where Δt is a typical time step in the calculation, is also shown in Fig. 5.

Asay, Chhabildas and Wise [9] have also estimated an effective viscosity for beryllium. They derive a model where ν varies as $\dot{\varepsilon}^{-1/2}$ For shocks greater than 25 GPa, the experimental resolution limits their ability to measure $\dot{\varepsilon}_p$. However, within range $3 < \dot{\varepsilon}_p < 60$, their model agrees well with their data. These results are also shown in Fig. 5.

Comparing the results from the two models, we see that they can differ by more than an order of magnitude. However in the range of $3 < \dot{\varepsilon}_p < 60$, the agreement is better than a factor of 4. Walters [12] in his review of viscosity, notes that differences of 2 to 3 orders of magnitude in estimating effective viscosity is not unknown. Consequently, the agreement between these two models seems more striking than their disagreement.

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FIGURE 1 - Yield strength vs. true strain

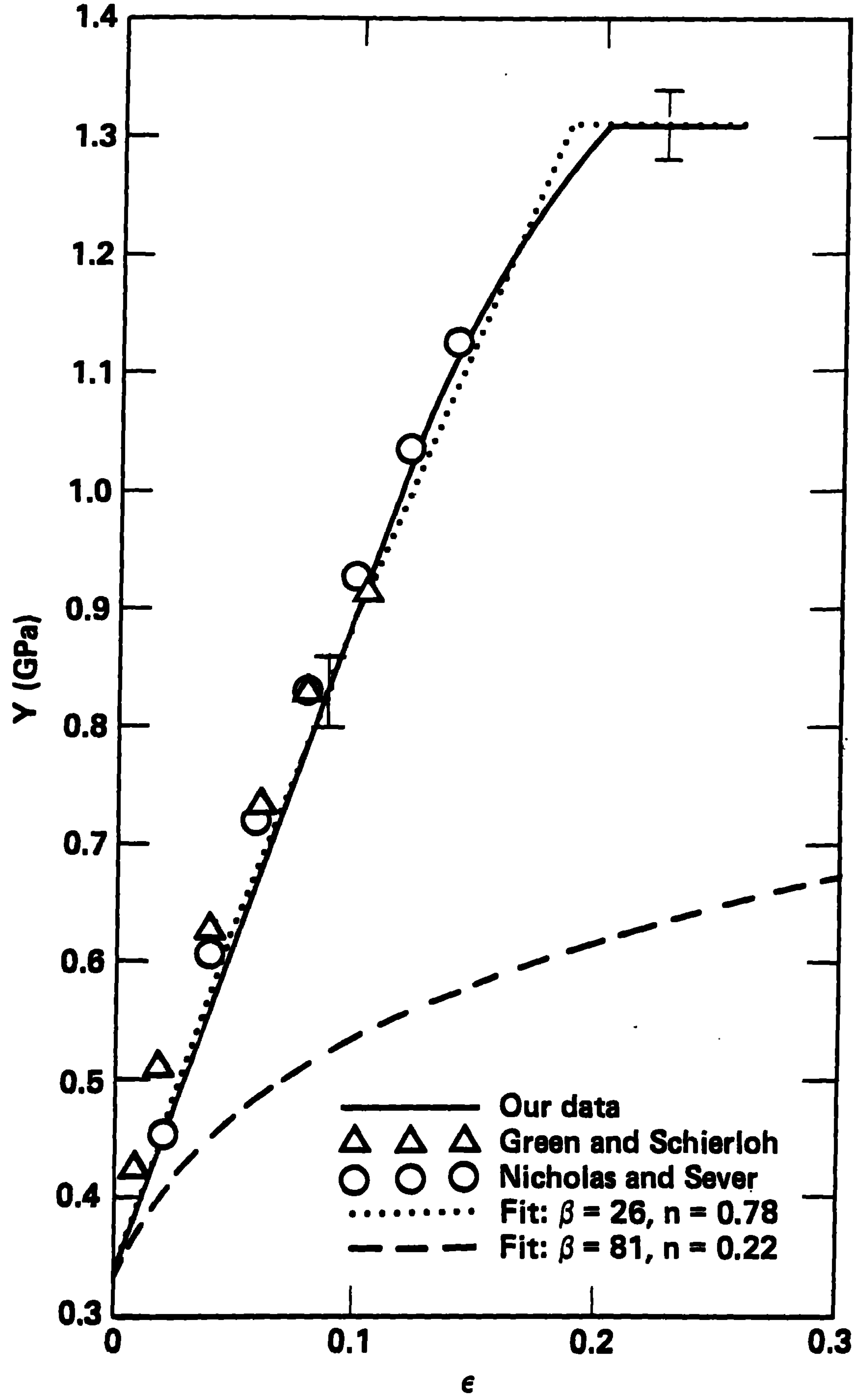


FIGURE 2 - Interface velocity vs. time (peak stress = 34.4 GPa)

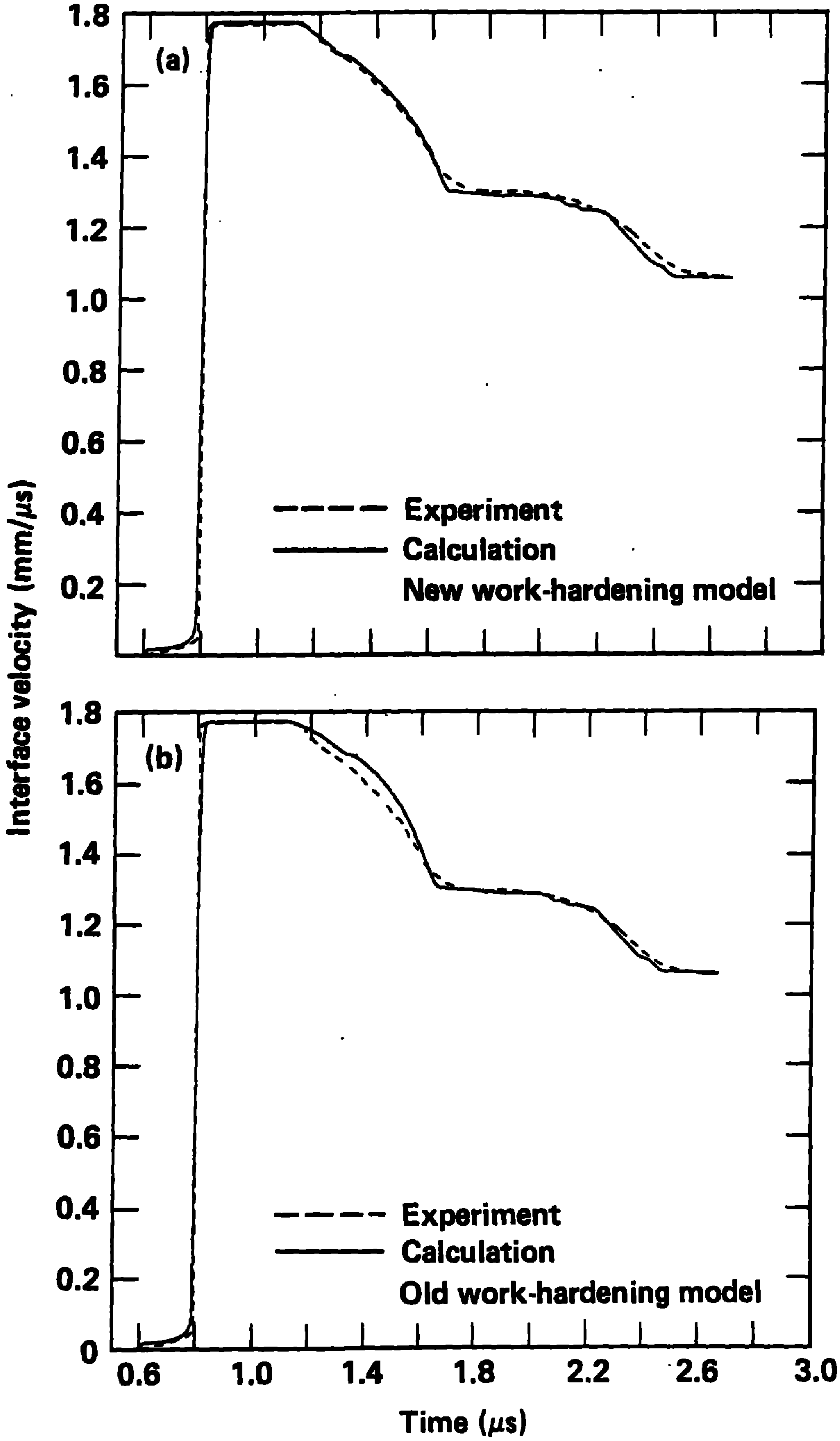
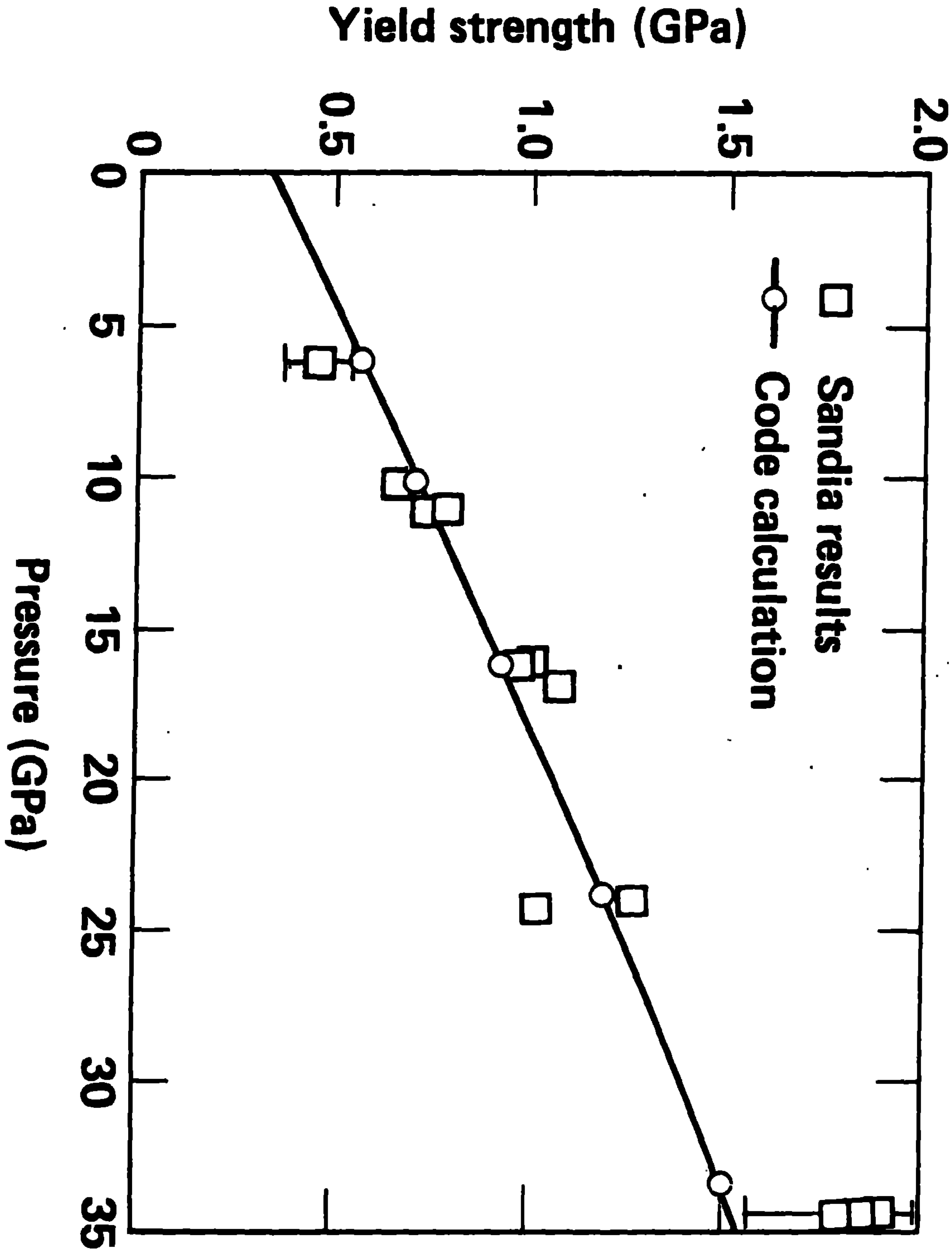


FIGURE 3 - Yield strength vs. peak
initial pressure



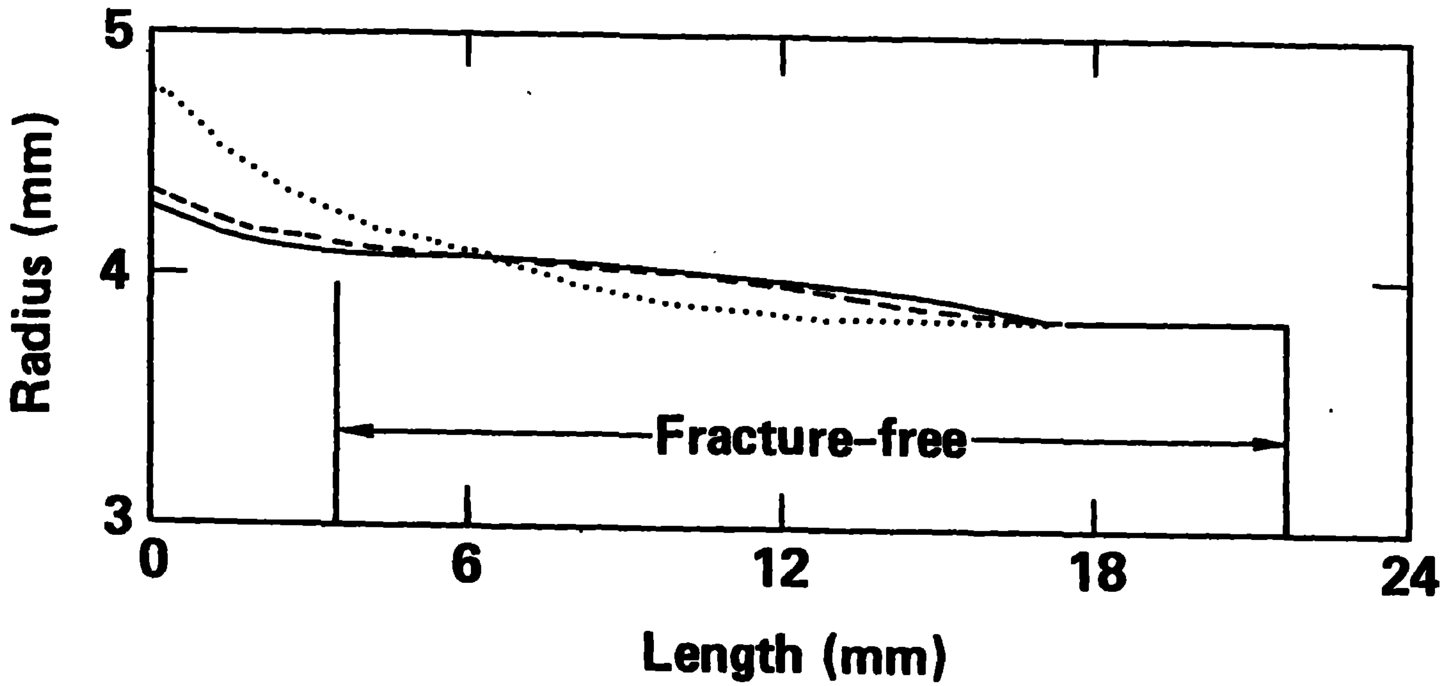


FIGURE 4 - Comparison of experimental profile of deformed cylinder (---) and calculations. New model (——); old model (...). Radial magnification is 4.6 and the zero is suppressed.

FIGURE 5 - Effective viscosity vs.
peak strain rate